HEAT MINING TO EXTRACT HOT DRY ROCK (HDR) GEOTHERMAL ENERGY: TECHNICAL AND SCIENTIFIC PROGRESS

David V. Duchane
Los Alamos National Laboratory

Professor Daniel Swenson
Kansas State University

KEY WORDS

GEOCRACK, HDR, hot dry rock, reservoir modeling, reservoir engineering, reservoir lifetime, thermal drawdown, tracers.

PROJECT BACKGROUND AND STATUS

The technology to extract energy at useful rates from the large, ubiquitous hot dry rock (HDR) resource originated in the early 1970's, and was disclosed in a patent issued to the Los Alamos National Laboratory in 1974 (now expired). A small HDR reservoir was constructed at Fenton Hill, NM during 1974-1978, and operated intermittently from 1978-1980 to prove the scientific feasibility of extracting energy from HDR. During 1980-1986, a larger, deeper, and hotter HDR reservoir, the Phase II reservoir, was developed at Fenton Hill.

Between 1987 and 1991, a surface plant, designed to power-industry standards and capable of extended operation, was constructed and mated to the Phase II HDR reservoir. That plant was operated in a series of flow tests conducted between 1992 and 1995. Earlier Research Updates have documented the results of these tests. The USDOE ordered the decommissioning of the Fenton Hill HDR site in Fiscal Year 1996. The 1992-1995 flow-test results thus represent the end of field experimentation on HDR technology at Fenton Hill for the foreseeable future.

Over the past few years, the results of the Fenton Hill flow tests have been applied to improve the GEOCRACK reservoir model. This model is being developed by Kansas State University to more closely simulate the behavior of the reservoir at Fenton Hill during both steady-state and transient flow operations. During 1994, temperature calculations were coupled to the hydraulic and mechanical computations of GEOCRACK in order to enable the model to predict the thermal effects of reservoir operations. GEOCRACK advances in 1995 included improvements in simulating reservoir flow paths by 1) the incorporation of a variable “fluid height” parameter that gives the model quasi-3D characteristics, and 2) a “far field” factor that increases the ability of the model to replicate transient fluid storage. These improvements and others continue to increase the value of GEOCRACK in the simulation of HDR and other geothermal reservoirs. By the end of 1995, worldwide interest in GEOCRACK was growing significantly, both in HDR circles and in the wider hydrothermal modeling community.

Simulations conducted with the modified version of GEOCRACK have indicated that a large cooled region would develop after 40 years of circulation at Fenton Hill under conditions similar to those employed in recent flow testing, but the cooling front would not have reached the production wellbore even after such a long term of continuous operation. In addition, GEOCRACK calculations have shown that the flow rate through the reservoir at a constant applied pressure would at first decline, but after about a year would begin a period of continual increase. Unless restrained by active intervention, this flow increase would eventually lead to short circuiting. In brief, GEOCRACK, as modified to include thermal performance, predicts a long thermal lifetime and constantly improving productivity for the Fenton Hill HDR reservoir and, by implication, for similar HDR reservoirs that may eventually be developed around the world.

PROJECT OBJECTIVES

Technical Objectives

- Work with the private sector and other interested parties to apply HDR technologies to increase the output and efficiency of hydrothermal reservoir operations.
- Work with private industry to develop niche HDR applications where and when opportunities can be identified.
- Conduct collaborative interactions with international HDR programs in Japan, Europe, and elsewhere.

Expected Outcomes

- HDR technologies should help the geothermal industry remain a competitive power source.
- Niche applications may help to document the economic factors associated with energy production from HDR and set the stage for more widespread implementation of the technologies.
- Foreign collaborations should keep the United States involved in experimental HDR work during a period when no large-scale US field operations are possible and thereby contribute to maintaining a base of HDR technical expertise in the US.

APPROACH

The HDR Program was in the process of being restructured by the US DOE throughout FY 1996. The DOE first disclosed its intention to restructure the HDR Program during a presentation at the Geothermal Resources Council Annual Meeting in October 1995. At the same time, the Department announced the cancellation of the solicitation for an industry-led HDR project to produce and market energy derived from an HDR resource.. These actions were followed later that same month by a memo to Bruce Twining, Manager of the Albuquerque Operations Office (ALOO), from Allan Jelacic, Director of the DOE Geothermal Division, formally requesting that ALOO work with Los Alamos personnel to decommission the Fenton Hill HDR site. A draft decommission plan was subsequently prepared for ALOO by Los Alamos, and presented to Geothermal Division management in January 1996. Because of the site's imminent shutdown, only a few essential field experiments were conducted at Fenton Hill in 1996. Technical development work was concentrated on improvements in reservoir modeling, and on consolidating the field data accumulated during the previous four years of field testing to provide a coherent picture of the behavior of the Fenton Hill HDR reservoir under a variety of operating scenarios.

RESEARCH RESULTS

GEOCRACK Reservoir Modeling Advances

Introduction. GEOCRACK is a fully-coupled rock-deformation/fluid-flow/thermal-drawdown model that has been developed to simulate and predict the behavior of HDR reservoirs under a variety of conditions. GEOCRACK has been continually modified to faithfully replicate the actual conditions observed during flow testing at Fenton Hill. It has also been applied to predict future reservoir performance under a number of operating scenarios.

The correlation of GEOCRACK simulations with real data from Fenton Hill was first reported in the 1994 Federal Geothermal Research Program Update. That same report summarized the results of initial GEOCRACK thermal simulations that indicated rapidly increasing productivity as an HDR reservoir cools, and predicted an extremely long lifetime (>40 years) for the Fenton Hill reservoir under the operational conditions of the recent flow testing (100 gpm production). The 1995 Update reported improvements in GEOCRACK that incorporated a quasi-3 dimensional height parameter to more realistically model reservoir flow paths and a "far field" factor to more adequately account for fluid storage.

Code Upgrades. The GEOCRACK code was modified during 1996 by incorporating algorithms that both broadened the range of application of the code and increased its operating efficiency. Some of the specific improvements are as follows:

1. The time step control was improved to facilitate the modeling of situations with variable time steps. The user is now able to produce plots at a variety of precise times over the duration of the modeled events.

2. Axisymmetry was incorporated for the reservoir structure, fluid, and thermal analyses.

3. Equations for density variations were derived and subsequently fluid density as a function of temperature and pressure was added to make it possible to realistically model natural circulation with GEOCRACK.

4. The mesh generation capabilities of GEOCRACK were improved to provide more flexibility in modeling various reservoir joint configurations.

5. Tracer simulation capabilities were improved to allow modeling the behavior of thermally reactive and absorbing tracers.

6. Development of a truly 3-dimensional HDR reservoir model was begun. The 3-D model will be derived from GEOCRACK and will incorporate both its wide range of applications and its operational efficiencies.

Simulations of Reservoir Operations and Thermal Drawdown. Table 1 illustrates the capability of GEOCRACK to faithfully model the production results from a variety of actual test conditions at Fenton Hill.

Note that there is generally good agreement between the observed production rates and the modeled production rates at several imposed injection pressures. This agreement was achieved by incorporating inclined flow paths into the established model mesh that could be specified to open at pressures intermediate between the two principle stresses. It is believed that this added feature of the model is more analogous to the actual joint configuration at Fenton Hill than the more rudimentary design incorporating only horizontal and vertical joints.

Using excellent Fenton Hill simulation results, GEOCRACK was further applied to evaluate the optimal flow rate for useful heat extraction from a Fenton Hill-type reservoir. This modeling produced thermal drawdown results that generally agreed with other models that have been used to predict Fenton Hill thermal performance. These modeling results were taken one step further than in previous studies, by integrating the total thermal energy production over ten years of operation at temperatures above 150°C and 100°C, respectively, as a function of various flow rates. The results of this integration showed that production rates of 64- to 80-gpm produced more useful energy for electricity generation (assuming 150°C as the lower limit for useful energy production), than either lower or higher flow rates (Fig. 1). This simple illustration, shows the potential of models such as GEOCRACK to provide a means for optimizing the productivity of a geothermal reservoir over a predetermined lifetime, a lifetime which may itself be determined by financing, contractual, or other business obligations.

Work this year also showed the potential for applying GEOCRACK to model a reservoir that may have numerous flow paths, each with a different flow path geometry, thus more closely replicating what are likely to be the flow conditions in real geothermal reservoirs. Different flow path geometries imply different flow rates and, consequently, different cooling patterns. Figure 2 shows a GEOCRACK simulation of the thermal drawdown of a reservoir with two different flow-path geometries. The drawdown profile varies from the smooth curve typically obtained in models based on uniform-joint assumptions, and points out the potential for applying GEOCRACK to analyze the behavior of real reservoirs with many significantly different flow paths. These results indicate that GEOCRACK, when used in conjunction with reservoir analysis tools such as wellbore logging and tracer measurements, may be useful in generating an accurate picture of the future performance of real geothermal reservoirs under a variety of operating scenarios.

The GEOCRACK applications reported above are discussed in much more detail in a paper presented at the 1996 Stanford Geothermal Conference (DuTeaux et al 1996).

Simulations of Reactive Tracers. A major advantage of GEOCRACK in predicting the behavior of tracers in a geothermal reservoir is the incorporation of a particle-tracking algorithm that takes into account both the overall fluid-flow rate and the time-dependent dispersion of the tracer in the fluid as it traverses the reservoir. This simulation of tracer behavior has been further enhanced by incorporating additional algorithms to simulate thermally reactive and absorbent tracers. These algorithms utilize reaction-rate constants and retardation factors specific to each individual tracer material, and are obviously greatly influenced by the ratio of volume to surface area in each fluid element.

By using multiple tracers in a single experiment, the reservoir surface areas and/or thermal profiles can be assessed. This assessment compares the return patterns of adsorbent and/or thermally active tracers with those of a non-reactive tracer which serves as an internal standard in a fashion directly analogous to many chromatographic analytical techniques (Figs. 3 and 4). Adsorbent tracers (Fig. 3) would be expected to show a return profile in most aspects similar to the standard, but delayed in time as a function of the surface area and specific adsorbency of the tracer. On the other hand, thermally reactive tracers (Fig. 4) would show return patterns similar to the standard on a time scale, but reduced in concentration by an amount proportional to the reservoir temperature profile and the reactivity of the tracer.

By employing multi-component tracers repetitively, a picture of changing flow patterns or advancing cooling fronts in geothermal reservoirs could be developed. GEOCRACK could then use these data as the basis for predictive modeling that might anticipate thermal breakthrough or fluid depletion. A well-designed multi-component tracer-testing program is proving to be essential to maintaining productivity in hydrothermal reservoirs. It could be the most useful technology available for designing and evaluating the reinjection efforts that are integral to HDR operations and are rapidly becoming essential in hydrothermal field management..

Fenton Hill Reservoir Surveillance Data

Major field work on HDR in the United States was terminated as part of the DOE directive to decommission the Fenton Hill HDR Pilot Facility in October 1995. As decommission activities proceeded, however, the deep Fenton Hill reservoir was monitored periodically to provide as much documentation as possible of the final days of the world’s most advanced HDR system. The monitoring consisted of periodic wellbore logs and regular measurements of the reservoir pressure.

Wellbore logging results. Temperature logs of the production wellbore were conducted on October 18, 1995 and January 10, 1996. The October log showed that the temperatures in that portion of the wellbore above the production zone had decreased toward the pre-existing geothermal gradient after production was terminated in July 1995. It also indicated a wash-out of the temperature profile previously observed across the production interval, with the fluid-producing fractures being somewhat less clearly delineated by temperature anomalies than during logs performed while flow testing was underway.

The January log was conducted at an ambient reservoir pressure of just over 600 psi. That log indicated a continuing recovery of the temperatures in the reservoir region of the production wellbore back toward the natural geothermal gradient; the deepest part of the profile through the reservoir zone (below 11,800 ft) exhibited warming and the shallower portion cooling. From the surface to about 9,000 ft, the wellbore temperature profile appeared to follow the previously measured geothermal gradient, indicating almost total recovery from the local heating that took place during the May-July 1995 flow test.

Logs of the injection wellbore during the early part of Fiscal Year 1996 were carried out primarily to determine the location of a breach that had been observed in the 9-5/8-in. wellbore casing. A comparison of shut-in and flowing temperature logs, conducted in October and November 1995, respectively, clearly indicated the location of the breach, and demonstrated the utility of this two-log technique for investigating wellbore problems of this type (Fig. 5).

A subsequent log on December 14, 1995 showed about a 5°C radial-conductive recovery toward the normal geothermal gradient in the portion of the injection well extending down to 10,400 ft. From that point down to the primary injection zone at 12,000 ft, the indicated recovery was more on the order of 15-16°C, suggesting a significant convective enhancement of conductive recovery, particularly up to about a depth of 11,000 ft. This convective recovery implied both that the fractured reservoir zone extended upward at least 1,000 ft from the main injection interval, and that thermal convection was still operating within this part of the reservoir, even at the very low reservoir pressures of 600-700 psi prevailing at the time of the December log.

Reservoir Pressure Monitoring. By the beginning of Fiscal Year 1995, the pressure on the Fenton Hill HDR reservoir had declined to about 860 psi from an average level of approximately 3,500 psi during the flow-testing period of the previous summer. Part of this decline was due to the escape of fluid via a leakage pathway in the injection wellbore. Interestingly, pressurization data indicated (at least at the pressure levels then prevailing) the reservoir consisted of two segments, a large portion connecting the two wellbores, and a somewhat smaller portion connected to the annulus of the injection wellbore. Pressure measurements indicated that there was only limited communication between these two segments. With the leakage pathway shut-in, the rate of pressure decline had decreased by January 1996 to only about 1 psi/day. The reservoir pressure continued to drop throughout the rest of the winter and early spring, reaching a level of about 420 psi by mid-May 1996.

On May 20, an active venting process was initiated to remove water from the reservoir in preparation for plug and abandon operations. More than 500,000 gallons of water were removed from the reservoir in a series of venting operations conducted over the next several months. During each venting episode, the reservoir pressure would rapidly decline, but in the intervening periods, when the reservoir was shut-in, the pressure would increase significantly as fluid from the overpressured, and relatively impervious, region beyond the periphery of the fractured reservoir flowed back into the reservoir itself. These observed pressure increases lend additional credence to previous assertions that most of the water that was apparently “lost” during circulation through the reservoir was in reality simply stored at high pressure in the microcrack fabric of the essentially impervious rock beyond the boundaries of the reservoir proper.

By the close of Fiscal Year 1996, the pressure on the large Fenton Hill HDR reservoir was holding steady at about 302 psi. Early in Fiscal Year 1997, the system was vented to zero pressure, and operations to plug and abandon the injection wellbore were completed. The production wellbore was held open by the Laboratory for use in a variety of future tool development and other field experiments.

FUTURE PLANS

GEOCRACK Model Development

Modeling work will focus on both increasing the applicability and use of GEOCRACK for hydrothermal reservoirs and continuing the development of GEOCRACK3D. For the hydrothermal industry, GEOCRACK has application in designing re-injection strategies, understanding tracer data, and predicting the long-term effect of reservoir cool-down on flow characteristics of the reservoir.

Specific developments of GEOCRACK will include: 1) the addition of porous flow in the rock blocks, 2) ease-of-use improvements (note that GEOCRACK is already fully interactive and graphical), and 3) the addition of interactive help functions. To broaden the use of GEOCRACK, training sessions will be offered at an appropriate international geothermal venue.

HDR Technology Development

The HDR Program will pursue a three-pronged effort involving transfer of existing HDR technology to the private sector, exploring niche opportunities for HDR implementation, and collaborating in international HDR projects. Technology transfer will entail 1) formulating joint projects to apply HDR technology in non-HDR hydrothermal situations, and 2) outreach events directed toward providing specific techniques and processes to the wider hydrothermal and general private-sector community. Niche HDR opportunities may exist in selected domestic and overseas markets, as part of co-generation schemes, or in other unique situations. All of these will be vigorously pursued. Finally, interactions with the established HDR programs in Japan and Europe will be continued.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Interest in GEOCRACK Modeling Work

Organization	Type and Extent of Interest
Energy and Geoscience Institute, Univ. of Utah	Tracer simulations
BGI, Consultants, USA	Reservoir simulation
Stanford University experiments	Analysis of flow in rock joint
Seoul National University Facility, Korea	Analysis of nuclear waste storage
Geoscience Research Institute flow	Modeling of glacier movement water
INGEOMINAS, Columbia	--------------------------
CRIEPI, Japan	HDR simulation
CSM Associates, UK	Reservoir simulation

This year GEOCRACK has been adapted for use on both computer workstations and PC's running Windows 95 or NT. The program can be downloaded from the web at site http:/www.engg.ksu.edu //~geocrack. Our observations indicate that the GEOCRACK web site is being accessed on a daily basis.

Interest in HDR Technology Per Se

Organization	Type of Interest and Status
Americulture	HDR Implementation-project in early discussion
Archer Edward Corporation	Development at Fenton Hill-dormant
CalEnergy Corporation	HDR Potential at Newberry Crater, OR-nascent
Clean Air Conversion Systems	Operating Fenton Hill-offer rejected by DOE
Envirocorp	Use of Fenton Hill deep wells-dormant
Environmental Energy Systems	Experiments at Fenton Hill-dormant
L/T International Consultants	HDR Implementation-project in formation
Plumas-Sierra Rural Electric Coop	HDR Development in northeast CA- in abeyance
Tricor Technologies	HDR Implementation-project in formation
United World College	HDR Implementation-project in formation

BUDGET DATA

Fiscal Year 1996 (including all Fenton Hill Decommission Work)		\$3.1 Million
Fiscal Year 1995		\$1.8 Million
Cumulative DOE Funding 1974-1996	Approx.	\$150.0 Million
Cumulative Foreign and other Funding 1974-1996	Approx.	\$27.7 Million
Grand Total Program Funding	Approx.	\$177.7 Million

REFERENCES

Duchane, D.V., 1996. Heat Mining to Extract Hot Dry Rock (HDR) Geothermal Energy: Technical and Scientific Progress. Federal Geothermal Research Program Update Fiscal Year 1995, p 4-215 to 4-231.

Duchane, D. V., 1995. Heat Mining to Extract Hot Dry Rock (HDR) Geothermal Energy: Technical and Scientific Progress, Federal Geothermal Research Program Update Fiscal Year 1994, p 4-197 to 4-204.

DuTeaux, R., Swenson D., and Hardeman, B., 1996. Insight from Modeling Discrete Fractures with GEOCRACK: a Geothermal Reservoir Model, Proceedings of Twenty-First Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, p 287-293

DuTeaux, R., Swenson, D., and Hardeman, B., 1996. Modeling the Use of Reactive Tracers to Predict Changes in Surface Area and Thermal Breakthrough in HDR Reservoirs, Proceedings of the 3rd International HDR Forum, Santa Fe, NM. (Proceedings available from J. Benson, MS-D442, Los Alamos National Laboratory, Los Alamos, NM.)

DuTeaux R., and Callahan, T. J., 1996. Comparing Reactive and Non-Reactive Tracers to Measure Changes in Liquid-Dominated, Fractured Geothermal Reservoirs, Geothermal Resources Council Transactions, Vol. 20, p 447-451.

Swenson, D., DuTeaux R., and Sprecker T., 1995. Modeling Flow in a Jointed Geothermal Reservoir, Proceedings of the World Geothermal Congress 1995, p 2553-2559.

CONTACTS

Geothermal Technologies Office
HDR Program Manager

Ms. Gladys Hooper
Department of Energy
EE-12
Forrestal Building
1000 Independence Avenue, S.W.
Washington, DC 20585

DOE Albuquerque Area Office
HDR Program Manager

Dan Sanchez
Energy Projects Manager
Energy Technologies Division
US Department of Energy
P.O. Box 5400
Albuquerque, NM 87185

Los Alamos HDR Program

Dave Duchane
Los Alamos National Laboratory
P.O. Box 1663
MS D443
Los Alamos, NM 87545
Phone: 505 667-4318   Fax: 505-667-8487

Kansas State University
GEOCRACK Development Group

Professor Daniel Swenson
Department of Mechanical Engineering
Durland Hall
Manhattan, KS 66506-5105
Phone: 913-532-2320   Fax: 913-532-7057

Table 1

Comparison of Observed Flow Rates with Flow Rates Predicted by GEOCRACK

Injection Pressure (psi)	Production Backpressure (psi)	Observed Flow Rate During Fenton Hill Testing (gpm)	Flow Rate Predicted by GEOCRACK Model (gpm)
3960	1400	89.2	89.2
3960	1800	90.2	88.2
3960	2200	82.2	82.2
3248	1400	60.5	48.6
2475	1200	23.8	23.8